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On the Overstraining of Iron by Tension and Compression.[*]

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The experiments about to be described were undertaken with the view of throwing some light on the uncertainty which seems to exist as to the effect produced by tensile overstrain on the behaviour of iron when afterwards subjected to compression. As long ago as 1848, Professor James Thomson called attention to this question,[†] but although much experimental work has been done since then, the following quotations should serve to justify the proposed line of research. In Thurston's "Iron and Steel" (1891), it is stated that "it has been shown that the exaltation of the elastic limit in iron is not confined to the direction of the strain produced, but that it affects the metal in such a manner as to give it an exalted elastic limit with respect to subsequent strains however applied. Thus the engineer may . . . . strain his bars in tension to secure stiffness in either tension or compression, or transversely, or he may give his bars a transverse set to obtain a higher elasticity in all other directions." Ewing, in his "Strength of Materials" (1899), writes: "It may be concluded that when a piece of iron or steel (and probably the remark applies to most other metals) has been overstrained in any way—that is to say, when it has received a permanent set by the application of stress exceeding its limits of elasticity—it is hardened in the sense of being rendered less capable of plastic deformation." On the other hand, in Johnson's "Materials of Construction" (1900), the statement may be found that, "Both wrought iron and rolled steel in their normal state have 'apparent elastic limits' in tension and compression numerically about equal. If this material be stressed much beyond these limits, however, in either direction, its elastic limit in this direction is numerically raised to about the limit of the greatest stress, while the elastic limit in the opposite

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[*] Being a note in continuation of previous papers:—
"On the Recovery of Iron from Overstrain," 'Phil. Trans.,' A, 1899.
"On the Tempering of Iron hardened by Overstrain," 'Phil. Trans.,' A, 1902.
"On Changes in Elastic Properties produced by the Sudden Cooling or 'Quenching' of Metals," 'Roy. Soc. Proc.,' August, 1902.
"On the Effects of Tensile Overstrain on the Magnetic Properties of Iron," J. Muir and A. Lang, 'Roy. Phil. Soc. Glasgow Proc.,' January, 1905.

[†] 'Cambridge and Dublin Mathematical Journal,' November, 1848, or article, "Elasticity," 'Encyclopædia Britannica.'

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direction is greatly lower or even reduced to zero." Practically the same view is taken in Unwin's "Testing of Materials of Construction" (1899), with the addition that "the elastic limits of a material are variable limits, restricted only by this, that the range of perfect elasticity seems to be a fixed range." In an account of Bauschinger's work, given in the 'Proceedings of the Institution of Civil Engineers' (Vol. 87), the statement as to the effect of tensile overstrain in lowering the elastic limit in compression to zero is also to be found, with the curious addition that "time in these cases has little effect."

It is possible that some or all of these statements may be reconciled, but it is thought that the experiments about to be described show, at least, that further research is desirable. The experiments, although mainly performed more than three years ago, are merely of a preliminary character; but as the present writer does not see his way at present to continue the research, it is hoped that the publication of the results so far obtained may lead to the work being taken up by some other experimenter.

Before describing the compression experiments it will be necessary to consider the behaviour of iron or steel when subjected to tension tests. This probably will be done best by means of an ideal diagram, the object of the research being not so much to find what is the actual behaviour of a more or less imperfect specimen when subjected to more or less imperfect tests, as to find what is the characteristic behaviour of thoroughly good material.

Diagram No. I, which has been modelled on experiments described in previous papers,* illustrates the elastic properties of a rod of mild steel subjected to a series of tension tests. Starting with the rod in a thoroughly annealed condition, Curve No. 1 may be taken as illustrating the primary elastic condition of the material. From the curve we see that Hooke's law is supposed to have been obeyed right up to the yield-point, which occurs at the stress of 20 tons per square inch. Many writers lay great stress on the distinction between the elastic-limit and the yield-point in iron, but as the elastic-limit was found to coincide with the yield-point in two or three actual experiments in which extensions were measured to the 1/400000 part of the length under test, it is thought unnecessary to indicate any gradual departure from Hooke's law. The yield-point indicates an important property of the material, whereas the position of the elastic-limit probably depends largely on the degree of accuracy to which measurements are made, and possibly indicates rather an imperfection of the material or of the specimen under test, than a definite property of matter.

To return to Curve 1, Diagram I, the large permanent extension which occurred at the yield-point is supposed to have been 2 per cent. of the length under test, and the whole extension is supposed to have occurred without alteration of the stress. It is thought that the following represents what would occur at the yield-point. At the stress of 20 tons per square inch some little portion of the material would yield. Before this little portion

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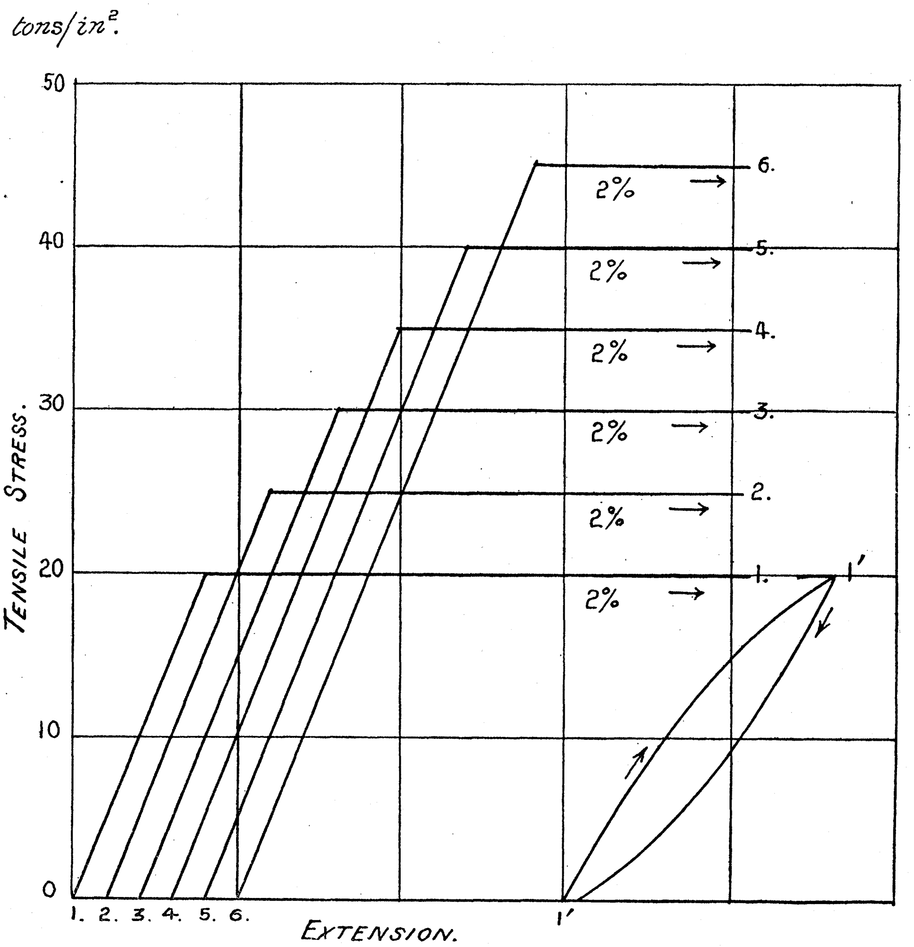
* *E.g.*, see pp. 6, 18, 'Phil. Trans.,' A, 1902.

DIAGRAM No. I.



(The curves should all start from the same origin.)

could again withstand the stress of 20 tons per square inch it must be allowed to stretch 2 per cent. of its length; hence there would be an instantaneous redistribution of stress across the section containing the element considered, the adjoining elements having temporarily a greater stress applied to them. If the material be homogeneous these adjoining portions must yield and the action would be transmitted piecemeal throughout the bar until the

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whole had extended 2 per cent. It is evident that the total load could be reduced somewhat without causing the yielding to cease once it had started, but such reduction would not imply a lowering of the yielding stress. Hence the extension at the yield-point has been represented by a horizontal straight line. The stress-strain curve at the yield-point is usually shown of a more or less erratic form, due probably to imperfections of the material and to the rate of loading; in the present paper all curves represent static tests. The extension of 2 per cent. which is supposed to have occurred at the yield-point in Curve 1, is the least permanent extension which could be given to the bar. Of course, the load could be removed after an extension of, say, 1 per cent. had occurred, but that would mean that only one-half of the bar had yielded, the other half being in the original elastic condition.

Immediately after the bar had been extended the material would be in a semi-plastic condition. This condition is illustrated by Curve No. 1′, Diagram I, which shows no elastic-limit or yield-point, but a gradually increasing departure from Hooke's law from the lowest loads.

If the bar be allowed to rest, a slow restoration of elasticity occurs, or if the specimen be heated to say 100° C., a complete recovery from the temporary effect of overstrain may be effected in a few minutes. This treatment is not to be confounded with the process of annealing, referred to later, which requires a much higher temperature and, roughly speaking, restores the material to its original condition. Curve No. 2, Diagram I, illustrates the elastic condition of the material after recovery from the overstrain produced by just passing the primary yield-point. The yield-point is shown to have been raised by 5 tons per square inch, and the extension which occurred at this raised yield-point is 2 per cent. as before.* The material after this second overstrain would be once more in the semi-plastic state, but if restoration of elasticity be again effected by warming, the yield-point would be raised by another "step" of 5 tons per square inch, the extension at the yield-point being again 2 per cent. This process of overstrain and recovery from overstrain is supposed to have been repeated five times (Curves 1 to 6, Diagram I), the bar finally fracturing at the stress of 45 tons per square inch, the total extension being 12 per cent., neglecting the local extension at the fracture and supposing the last extension which occurred at a yield-point to have spread throughout the length under test before the neck formed at which ultimately fracture occurred. Had the bar under consideration been broken in the usual fashion, that is, by continuous loading without allowing recovery from overstrain to take place, the breaking stress might have been, say, 35 tons per square inch, the ultimate extension perhaps 20 per cent., still neglecting local extension.

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* This "step" by which the yield-point is raised and the extension which occurs at a yield-point vary largely with the quality of iron or steel employed. Steps of from below 2 to 11 tons per square inch and extensions of from under 1 to 4 per cent. have been observed by the author.

Taking, then, Diagram I to represent the behaviour of a bar of steel when subjected to successive tension tests, the question arises as to how the compression yield-point varies in correspondence with the step-by-step rise in the tension yield-point. It may be granted* that immediately after tensile overstrain "the elastic-limit in compression is reduced to zero"; the elastic-limit in tension (not the yield-point) is similarly reduced. But, after recovery from overstrain, is the compression yield-point raised or lowered? If the rise in the tension yield-point be supposed to be due to some sort of internal stress set up by the process of recovery from overstrain, then it might naturally be expected that the compression yield-point should be lowered by a step equal to the rise in the tension yield-point. But the range from zero stress to the yield-point in compression cannot be so lowered step-by-step as the tension yield-point is raised (thus maintaining a "fixed range of elasticity"), or ultimately there would result a material having a very large range of elasticity in tension, but yielding under less than no load in compression, seeing that the yield-point in tension may be raised to more than double its original amount.

The Material Employed.

The compression experiments were all carried out with specimens from a single bar of steel about $10\frac{1}{2}$ feet long and $1\frac{1}{2}$ inch square section. The square section was chosen, as it was intended to test by means of little cubes the elastic properties in the transverse as well as in the longitudinal direction. The steel was supplied as very mild and thoroughly annealed, yet, although one portion of the bar yielded in tension at 17 tons per square inch, another portion received no permanent set even under the high load of 27 tons per square inch. This condition of affairs might well have led to disastrous results had the bar been employed for structural purposes. The hardest portion of the bar was exactly where the maker's name was stamped, which leads one to wonder whether the bar could actually have been reheated to have the name affixed and then suddenly cooled or "quenched." Possibly the bar was simply chilled by the application of a cold die. A microscopic examination of the bar would have been interesting, but a suitable miscroscope not being to hand, the greater portion of the bar was sent

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[*] Or see the experiment described on p. 41, 'Phil. Trans.,' A, 1899.

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to a large engineering works to be thoroughly annealed in their annealing furnace. Here, again, there was disappointment. A portion of the bar which had yielded at 20 tons per square inch, and had been overstrained by a pull of 27 tons per square inch, was found, after having been returned as thoroughly annealed, to withstand a stress of 27 tons per square inch without yielding. Now, annealing after tensile overstrain ought to lower the yield-point to at least* its original value, and, by heating the portion in an ordinary chemical combustion furnace, and allowing it to cool slowly, a yield-point was got at 20 tons per square inch. Thus the material had not really been annealed by the process used by the engineers, who paid great attention to prolonged heating and slow cooling in ashes, but had little regard to the main consideration—temperature. The work was thus handicapped from the very start. It was not satisfactory to begin with a bar whose initial condition was so far from being uniform, as it was doubtful if such annealing as could be obtained with a small chemical furnace would ensure the attainment of homogeneous material.

The Apparatus Employed.

For the measurement of small elastic contractions a Ewing Compression Instrument was employed. The instrument was specially ordered by Professor Barr with view to research work of this kind. By its means a contraction of 1/125000 of an inch could be measured on lengths of specimen varying from 1¼ to 4 inches. The shortest length was always adopted, and a direct comparison being made with a Ewing 8-inch extensometer, practically absolute agreement was got between the two instruments. The compression instrument was found to be in every way satisfactory.

The main trouble in the experiments was found to be in the application of the compressive stress to the ends of the specimen. Power was obtained from the 100-ton testing machine of the James Watt Engineering Laboratory. What was required of the machine was that two rigid parallel planes should be pressed against the ends of the specimen and always remain parallel. Now, when no pressure was being applied by the machine, the compression plates (owing to slackness in fitting) were very far from being parallel, and, although it is probable that when in action parallelism was nearly attained, still, under small pressures, it could often be detected that the pressure was not being uniformly distributed over the ends of the specimen, although the ends had been planed as accurately as possible and tested with callipers. This trouble, in gripping the specimen between the compression plates, became much aggravated after a few tests had been made, as it was found that the plates became indented, in spite of the fact that the steel experimented on was very mild, and that millboard packing was inserted between the plates and the ends of the specimens. The insertion of millboard was, of course, not made with the view of protecting the machine plates, but in order to allow, if possible, free lateral expansion at the ends of the specimen under test. Several kinds of packing were tried, the best tests being obtained when the packing consisted of many sheets of paper—the leaves of an old exercise book.

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* Annealing after tensile overstrain may lower the yield-point below its original value, see p. 28, 'Phil. Trans.,' A, 1902.

The Experiments.

Diagram No. II illustrates what were, perhaps, the best compression tests obtained. The specimen employed was in the condition as supplied by the makers, and was 2½ inches long. The sides being rather over 1½ inches, the cross-sectional area was found to be 2·36 square inches. The ends of the specimen were carefully planed parallel to one another, and perpendicular to the length of the specimen. The sides were left in the condition in which they came from the maker, and so were coated with a smooth skin of blue oxide. The compression instrument was attached to the central length of 1¼ inches, the specimen was placed between the compression plates of the testing machine and load applied, first in increments of 1 and finally very slowly in increments of ¼ of a ton per square inch. Curve No. 1 of Diagram II was plotted from the readings taken, and it will be observed that Hooke's law has been accurately obeyed right up to the yield-point, which occurred at 21½ tons per square inch. Just after the load of 21½ tons per square inch was applied the compression instrument reading was 241, but shortly "creeping" was observed, and the skin of oxide began to spring off the specimen. By watching the oxide springing off, yielding was observed to spread piecemeal throughout the specimen, and finally the compression instrument showed a practically steady reading of about 2900, the load still being 21½ tons per square inch of original area. The load was increased to 22 tons per square inch to ensure that the specimen had yielded throughout, the final reading on the compression instrument being 3050. The shortening which occurred at the yield-point was thus rather over 1·7 per cent. of the length under test which indicates that the shortening which occurs at a yield-point in compression is approximately equal to the extension which occurs at a tension yield-point. A good tension test of the material in the condition as supplied was not obtained, owing to the heterogeneous nature of the bar, but the portion of the bar immediately adjoining the specimen used to obtain

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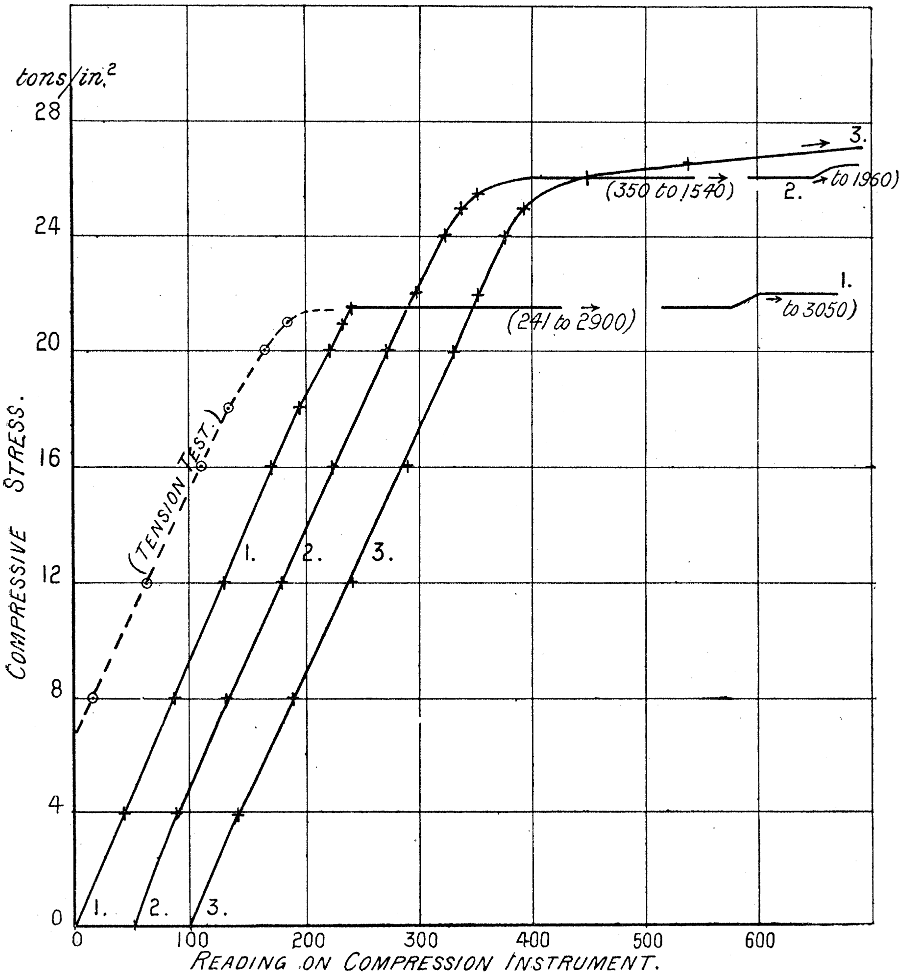
Diagram II (neglecting the short length required to grip a specimen in the tension grips) was found to yield at $21\frac{1}{2}$ tons per square inch, which agrees with the value of the compression yield-point.* The dotted curve in Diagram II illustrates a tension test of the material considered, and it will be observed that Young's modulus for tension and for compression has practically the same value.

Diagram No. II.



Scale.—1 unit = a shortening of 1/125000 of an inch on $1\frac{1}{4}$ inches.

The specimen was next removed from the testing machine and placed in boiling water for about 10 minutes. After cooling, the specimen was remeasured, the compression instrument was re-applied, and another test made, load being again applied in tons per square inch, of actual section. Curve No. 2,* Diagram II, shows that the yield-point has been raised to about 26 tons per square inch. This yield-point was by no means so definitely marked as the last, yielding practically stopping after a shortening of about 0·8 per cent. had occurred. The load was increased to 26½ tons per square inch, giving a shortening of about 1·1 per cent., but on examining the specimen it was found to have become distinctly barrel-shaped, the ends, owing, perhaps, to lack of freedom in the lateral direction, refusing to yield; so the load was not further increased. The specimen was removed, heated in boiling water, and then planed on the four sides to remove the central bulge. Another compression test was then made, and is illustrated by Curve 3, Diagram II. Had the specimen been overstrained throughout by the second loading, then it is thought probable that the next yield-point would not have occurred till over 30 tons per square inch had been applied. Curve No. 3 shows that considerable yielding was obtained at about 26 tons per square inch, practically at the same load as before—but a load of about 30 tons per square inch was required to produce a shortening equal to that which occurred at the primary yield-point. The load was increased to 32 tons per square inch, and on then examining the specimen it was found that the ends had expanded laterally, leaving the specimen hollow in the middle instead of barrel-shaped. This establishes the fact that the ends had not been overstrained by compression in the second test.

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* The extension observed at the tension yield-point was 0·08 or 0·09 of an inch on 4 inches, but should be less than this, as the yield-point was not well defined.

The experiments illustrated by Diagram II may be taken as agreeing with the known facts that Young's Modulus for tension and compression has the same value, and that in the normal condition of material the yield-points in tension and compression occur at practically the same intensities of stress. And further, the experiments show (perhaps not quite conclusively) that the shortening which occurs at a compression yield-point is equal to the extension which occurs at a tension yield-point, and that the yield-point in compression is raised by compressional overstrain by a "step" equal to the "step" by which the tension yield-point is raised by tensile overstrain.

The next set of experiments to be described were performed on the portion of material which had been overstrained (by a tension of 27 tons per square inch) and then annealed in a chemical combustion furnace. A compression specimen was cut from this portion of the bar, and the remainder of the portion was then subjected to a tension test. Large yielding started at 21 tons per square inch, but 23 tons per square inch of original area, or nearly 24 tons per square inch of actual stress, had to be applied before the yielding spread throughout the bar. Recovery from overstrain was effected, and a second compression specimen was cut from the bar thus overstrained. A second tension test was then made on the remaining portion of the bar, and a well-defined yield-point obtained at 27 tons per square inch. The load was not increased beyond the yield-point, but owing to the contraction in area due to the stretch at the yield-point, the material was subjected to an actual stress of about 27½ tons per square inch. Two more compression specimens were then cut, and recovery from overstrain effected.

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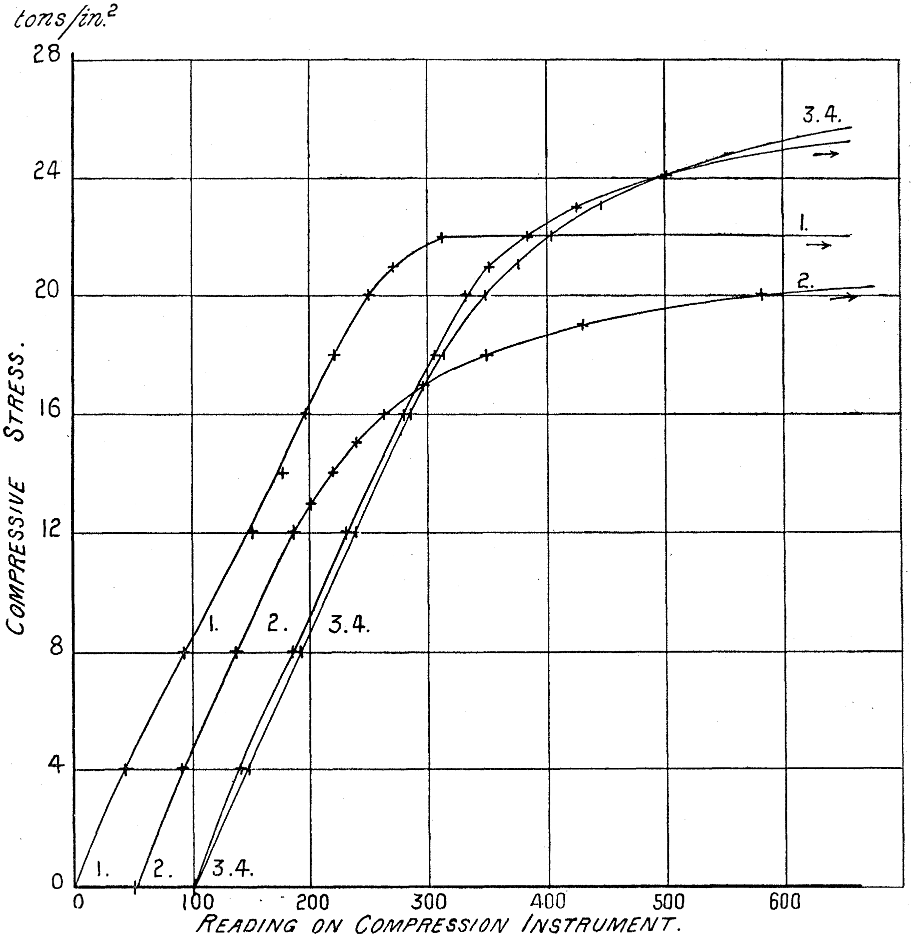
* The origin for the measurement of the shortening has been displaced, in order to avoid a confusion of the curves.

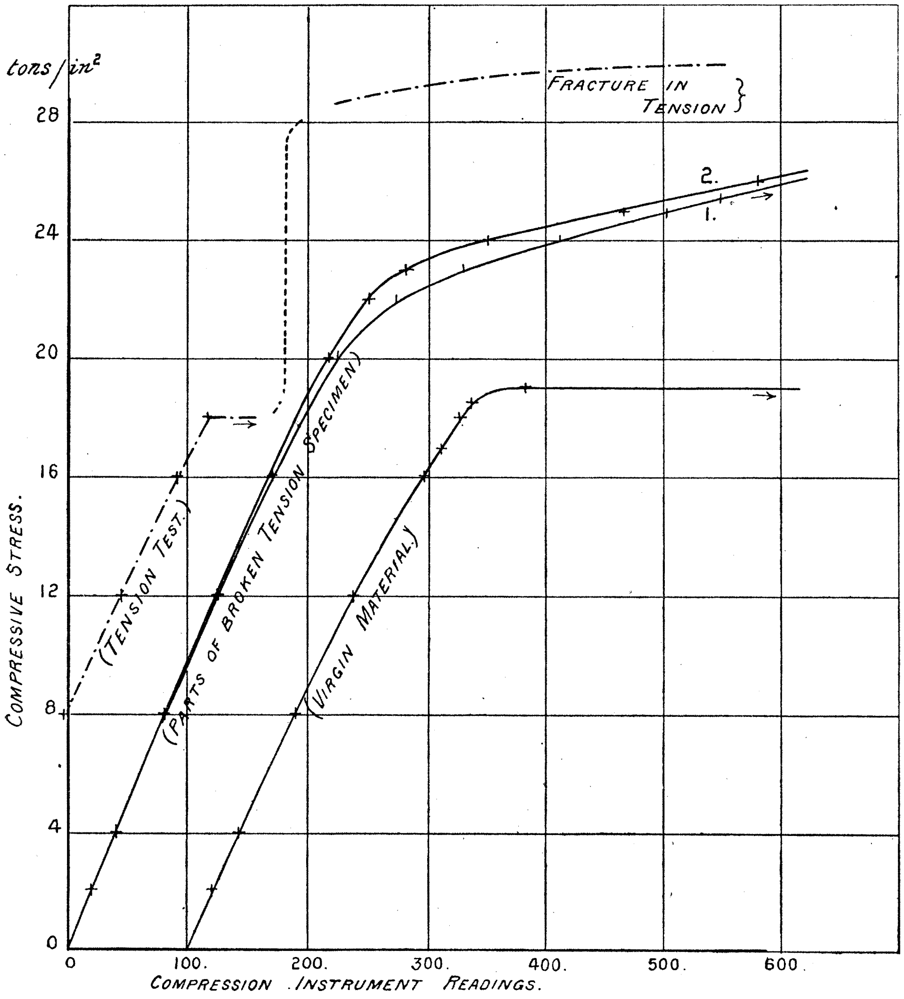
Diagram No. III.



Scale.—1 unit = a shortening of 1/125000 of an inch on 1¼ inches.

Diagram III illustrates the compression tests made on the four specimens just described. Curve 1 shows that in its original condition the material gave yield-points under tension and under compression at practically the same intensities of stress. Curve No. 2 is from an exceptionally bad test, due probably to imperfect gripping. The material was in the condition giving a tension yield-point at 27 (24+3) tons per square inch: the compression yield-point would be placed about 21 (24−3) tons per square inch. Curves 3 and 4 agree tolerably well, although they do not show very good yield-points. The position of these yield-points from an examination of

Diagram No. IV.



Scale.—1 unit = a shortening of 1/125000 of an inch on $1\frac{1}{4}$ inches.

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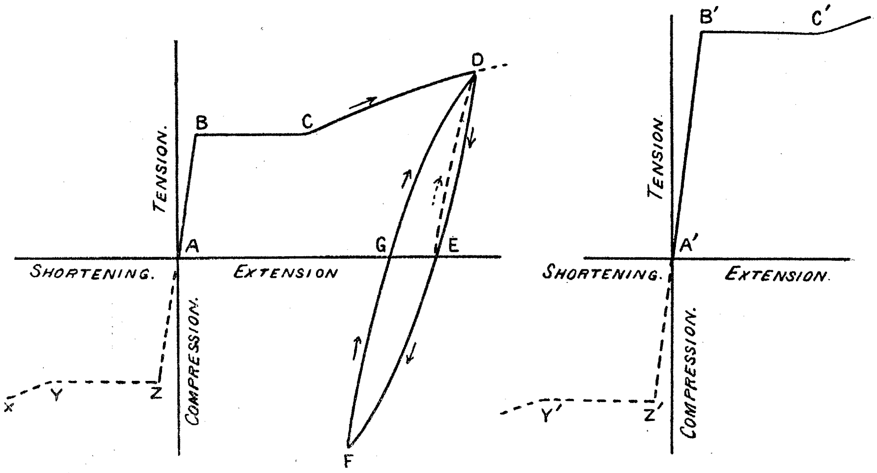
the curves would be placed about $24\frac{1}{2}$ ($27\frac{1}{2}-3$) tons per square inch. The material was in the condition which would give a yield-point under tension at $30\frac{1}{2}$ ($27\frac{1}{2}+3$) tons per square inch.

The last experiment to be recorded was performed with a portion of the bar in the condition as supplied by the makers. A tension specimen was strained in the testing machine until it broke under a load of about 30 tons per square inch of actual section. The extension was about 10·3 per cent., but the break occurred in the machine grips. Two compression specimens were cut from the bar which had been thus subjected to large tensile overstrain and recovery from overstrain was effected by warming. Curves 1 and 2, Diagram IV, illustrate the compression tests made. The material was in a condition which would have given a yield-point under tension at about 34 (30 + 4) tons per square inch; the compression yield-point seems to be rather over 26 (30 − 4) tons per square inch. The large tensile overstrain seems thus to have hardened the material very considerably as regards resistance to both tension and compression, although the resistance to tension is much greater than the resistance to compression.

The experiments just described, as well as several others performed in the course of this research, give some support to the conjecture that there are two distinct causes contributing to the phenomenon of hardening by tensile overstrain. The overstraining itself—the actual stretching of the material—seems to harden the material both as regards resistance to tension and to compression, while the process of recovery from tensile overstrain, by the application of an internal stress, raises the tension yield-point above the overstraining stress, but lowers the compression yield-point below the overstraining

DIAGRAM No. V.



stress by approximately an equal amount. A theoretical diagram (No. V) may help to make this conjecture clear. Suppose a specimen to be loaded in tension, then the stress-strain curve will be of the form A B C D. If the load be removed at D the curve may be continued, as shown by D E—the material being in the semi-plastic state. If now the load be supposed to be reversed and compression applied, the curve may be continued as shown by E F, the tensile overstrain being supposed to have hardened the material equally in both directions. The curve for compression will not be of the form indicated by A Z Y X, as the material is not in its "normal" condition. On removing the compressive stress the curve may be supposed to take the form F G, and on again reversing the stress the hysteresis cycle may be completed as shown by G D. If now recovery from overstrain be effected, elasticity is restored, the tension yield-point is raised by a definite "step" above D, while the compression yield-point is supposed to be lowered by an equal step below F. The curves A′ B′ C′ and A′ Z′ Y′ indicate the new elastic condition of the material. If this conjecture be correct then the positions of the compression yield-points may be determined, for each of the elastic conditions illustrated by Curves 1 to 6, Diagram I. In that diagram a specimen is supposed to have given yield-points in tension at 20, 25, 30, 35, 40 and 45 tons per square inch; the corresponding compression yield-points should occur at 10, 15, 20, 25, 30 and 35 tons per square inch.

Further experiments on the subject are, however, desirable, as the conjecture can scarcely be said to have been established. For example, it would be of interest to repeat the experiment of Diagram IV, endeavouring, however, to obtain a compression test with the material in the freshly overstrained condition, as well as in the condition after recovery from overstrain. By such a test it might be possible to show directly that recovery from tensile overstrain lowers the compression yield-point. Before further experiments are performed, however, new compression plates with spherical bearings and thoroughly hardened and polished faces should be designed for the testing machine.

The experimental work just described was mainly carried out by the author in the capacity of Research Student in the James Watt Engineering Laboratory.

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